The stellar velocity dispersion in the inner 1.3 disk scale-lengths of the irregular galaxy NGC 4449

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ABSTRACT

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We present measurements of the stellar velocity dispersion in the inner 1′ radius (1.3 disk scale-lengths) of the irregular galaxy NGC 4449 determined from long-slit absorption-line spectra. The average observed dispersion is 29±2 km s^{-1}, the same as predicted from NGC 4449's luminosity. No significant rotation in the stars is detected. If we assume a maximum rotation speed of the stars from the model determined from the gas kinematics of Hunter et al. (2002), the ratio V_{max}/σ_z measured globally is 3. This ratio is comparable to values measured in spiral galaxies, and implies that the stellar disk in NGC 4449 is kinematically relatively cold. The intrinsic minor-to-major axis ratio $(b/a)_0$ is predicted to be in the range 0.3–0.6, similar to values derived from the distribution of observed b/a of Im galaxies. However, V/σ_z measured locally is 0.5—1.1, and so the circular velocity of NGC 4449 is comparable or less than the velocity of the stars within the central 1.3 disk scale-lengths of the galaxy.

Subject headings: galaxies: irregular — galaxies: kinematics and dynamics — galaxies: structure — galaxies: individual (NGC 4449)

1. Introduction

The intrinsic shape of Magellanic-type irregular (Im) galaxies is controversial. Studies of the distributions of projected optical minor-to-major axis ratios b/a have been used to infer the intrinsic shape under the assumptions that there is one intrinsic shape and that galaxies are oriented at random on the sky. Hodge & Hitchcock (1966) and van den Bergh (1988) concluded that the intrinsic ratio $(b/a)_0$ of Im galaxies is 0.3–0.4 rather than the 0.2 value adopted for spirals. Staveley-Smith, Davies, & Kinman (1992), on the other hand, argue that the low ratio of rotation velocity to velocity dispersion often seen in the gas of irregulars must imply a thick disk with $(b/a)_0$ as high as 0.6. Yet others have interpreted the optical minor-to-major axis ratio distribution to mean that Im galaxies are triaxial in shape (Binggeli & Popescu 1995), only a little less spherical than dwarf ellipticals (Sung et al. 1998).

Fortunately, the stellar kinematics can be used as an indicator of the intrinsic shape of a galaxy, and so we began a program of observations of the stellar kinematics of Im galaxies. In 2000 January we used the Kitt Peak National Observatory (KPNO) 4 m Telescope with the RC spectrograph to measure the stellar rotational velocities in NGC 1156 and NGC 4449 (Hunter et al. 2002). In NGC 4449 we measured no organized rotation in the stars. By contrast, clear organized rotation is seen in the ionized and neutral gas.

NGC 4449 is not a pristine galaxy. It has interacted with another galaxy to produce large streamers of HI that encircle the galaxy (Hunter et al. 1998). In addition, the gas in the inner $2'$ of the galaxy is counter-rotating with respect to the gas at larger radii, also the signature of an interaction. We explained the gas and stellar rotations with a model in which the stars are in a disk seen nearly face-on, while the gas lies in a tilted disk with precession-induced twisting of the line of nodes.

This model is the simplest explanation that encompasses all the observations of NGC 4449. However, it is also possibile that more of the kinetic energy of the stars is in random motions rather than ordered rotation compared to the gas. If this were the case, it could have profound implications for the shape of the stellar disk.

The ratio V/σ is an indicator of how kinematically hot a system is, and, therefore, an indicator of its structure. Here V is the speed of rotation and σ is the velocity dispersion of the stars. Elliptical galaxies and dwarf ellipticals (dE), which are triaxial systems, have $V/\sigma < 1$ (Figure 4-6 in Binney & Tremaine 1987; Bender, Saglia, & Gerhard 1994; Pedraz et al. 2002; Pinkney et al. 2003) while spirals, which are cold thin disks, have $V/\sigma > 1$, usually 2–5 (Bottema 1993; Vega Beltrán et al. 2001).

The stellar velocity dispersion has been measured in only two Im/Sm galaxies until now: NGC 2552 (Sm; $M_B = -17.5$; Swaters 1999) and the LMC (Im; $M_B = -18.1$; van der Marel et al. 2002). In both systems the vertical velocity dispersion of the stars σ_z is $\sim$20 km s^{-1}. The relationship between integrated galactic magnitude M_B and central velocity dispersion σ_z or σ_R for spirals and NGC 2552 (Bottema 1993, Swaters 1999) predicts that the stars in galaxies with $M_B = -18.2$, such as NGC 4449, should have a velocity dispersion of 29 km s^{-1} if most of the kinetic energy of the stars is in ordered rotation.

Unfortunately, the spectral resolution of our earlier observations was not adequate to resolve the absorption profiles and allow a measurement of σ. Therefore, we undertook new observations of NGC 4449 with the Echelle spectrograph on the KPNO 4 m Telescope, which have a resolution that is 2.3 times higher. We present those observations here. We adopt a distance of 3.9 Mpc to NGC 4449.

2. Observations and Data Reduction

We observed NGC 4449 with the Echelle spectrograph on the KPNO 4 m Telescope during three nights in 2003 May. We used the UV camera, a Tektronics 2048 × 2048 CCD, and the 316–63° echelle grating. The cross-disperser was replaced with a silver flat in order to obtain a useful slit length of $3'$, and the slit width was $2.5''$. We used a narrow-band post-

slit filter (KPNO #1433, central wavelength of 5204 Å and FWHM of 276 Å) and GG495 as a pre-slit filter. The final spectrum covered 5050 Å to 5287 Å at 0.135 Å per pixel. The spectra included, therefore, the MgIb lines at 5167 Å, 5173 Å, and 5184 Å, which were the strongest absorption lines in the spectra. We binned by two in the spatial direction for a pixel scale of 1.22″.

NGC 4449 was observed at three position angles (PA): 46°, the morphological major axis; 316°, the minor axis; and 271°, plus 45° from the major axis. These are 3 of the 4 PAs (modulo 180°) that we used in our observations with the RC spectrograph. The slit was placed across the center of NGC 4449, determined from V-band images, by offsetting from a nearby star. However, we then nudged the position of the slit 4.3″ south in PA 316° and 0.2″ east and 1.8″ north in PA 271° to move the slit off the bright super star cluster near the galaxy center. Slit positions are drawn on V-band and Hα images of the galaxy in Figure 1. We took 5–6×1800 s spectra at each PA. Because NGC 4449 is bigger than the slit, we offset to a separate position to measure sky, and we sandwiched each galaxy observation between sky observations of equal integration time.

To remove pixel-to-pixel variations, we observed the white spot mounted inside the dome. The overscan portion of the CCD image was used to remove the electronic pedestal. Observations of Th-Ar comparison lamps were used to set the wavelength scale and map spatial distortions along the slit. A star observed at intervals along the slit was used to remove S-distortions. Finally, we observed 6–8 radial velocity standards of type F, G, and K each night from the United States Nautical Almanac (2003), and these were used as cross-correlation templates. Twilight sky provided a template of a G2V star.

The two-dimensional spectra were repixelized in order to impose a uniform wavelength scale and to correct for curvature along lines of constant wavelength and along lines of constant spatial position. We transformed to a logarithmic wavelength scale, subtracted sky, and combined the multiple images, rejecting cosmic rays.

3. Cross-correlation Measurements

Two of us undertook independent measurements of the heliocentric radial velocities and velocity dispersions in the spectra. In both approaches, one-dimensional galaxy and stellar spectra were extracted along the slit, and the continuum was fit and subtracted from each spectrum. The one-dimensional spectra were then cross-correlated against each of the stellar spectra observed on the same night, first the stars against themselves to look for systematic problems and then the galaxy spectra with the stars. We used the spectrum from

5134–5198 Å and 5205–5234 Å, excluding the region 5198–5205 Å because of the presence of galactic emission lines. Low frequencies resulting from residual continuum were removed with a step-function Fourier filter, and the peak of the cross-correlation profile was fit with a Gaussian.

The two approaches varied in the details of continuum fitting and Fourier filtering. In addition, in the first approach, D.A.H. extracted one-dimensional spectra summed every 24.4″. In the second approach, R.A.S. used one-dimensional spectra that had been boxcar-smoothed by 12.2″. Most of the measurements of the two approaches agree within the uncertainties. A few radial positions that do not agree within the error bars are undoubtedly due to the differences in sampling and the other details of the approaches, and perhaps better represent the overall uncertainties. We present the results of both measurements below: Approach 1 is plotted in blue and Approach 2 is plotted in red in the plots that follow.

The results of the cross-correlation—heliocentric velocity $V_{\rm helio}$ and FWHM of the profiles—obtained with all of the stars were averaged, regardless of the stellar type of the template. The uncertainty of each $V_{\rm helio}$ and FWHM was taken as the combination of the dispersion around the mean and the uncertainty in the fit, summed in quadrature, but the uncertainty in the fit dominates.

We measured an average central velocity of 205±1 km s^{-1}, where the uncertainty represents the night-to-night variation. The zero point of each night has been adjusted to the three-night average of the central velocity. In Hunter et al. (2002) the central velocity measured from the spectra was 214 km s^{-1}. To compare the current measurements with those made in 2002, we subtracted 9 km s^{-1} from each 2002 heliocentric velocity to give them the same central velocity as the current measurements.

To determine the observed velocity dispersion of the stars σ_{obs}, the FWHM measured from the galaxy profiles were corrected for the resolution given by cross-correlation of the template stars against each other, assuming that the FWHM add in quadrature. The average FWHM of the template stars was 47±1 km s^{-1} for the measurements in Approach 1 and 32 km s^{-1} in Approach 2.

4. Cross-correlation Results

4.1. Stellar rotation

Figure 2 shows the resulting heliocentric velocity $V_{\rm helio}$ as a function of position from the center of the galaxy. Positive numbers denote position along the slit in the direction

of the given PA. Included are the data from Hunter et al. (2002). Our new data cover approximately the inner $1'$ radius. This is 1.1 kpc at a distance of 3.9 Mpc or 1.3 optical disk scale-lengths, where the scale-length of 0.84 kpc is an exponential fit to V-band surface photometry measured by Hunter et al. (1999).

Hunter et al. (2002) reported no detectable rotation from the stars at any PA with an upper limit of $(3/\sin i)$ km s^{-1} kpc^{-1}. Our current measurements largely confirm this lack of observed rotation. However, at PA 271° the measurements plotted in red in Figure 2 do suggest a velocity gradient in the stars, and this gradient is intriguingly close to that measured for the ionized gas. A least-squares fit to the red points gives a velocity gradient of 9 ± 2 km s^{-1} kpc^{-1}. The measurements plotted in blue, which average over twice the spatial scale, lie within the uncertainties near the measurements plotted in red, but do not themselves show a velocity gradient. A fit to both sets of measurements yields a gradient that is half that seen in only the measurements plotted in red. Also, we do not see any hint of rotation at the other two PAs. By contrast, the amplitude of the velocity gradient for the ionized gas in our 2002 results was largest at a PA of 46°.

However, the uncertainties in the stellar $V_{\rm helio}$ at the three PAs are large and encompass several possibilities including no rotation of the stars or weak rotation with almost any kinematic major axis provided the inclination is not too large. For example, with the inclination of 68° and a kinematic major axis of 80° from our model for the kinematics of the inner HI gas, the gradient seen at PA 271° transformed to the other PAs would lie within the uncertainties of the $V_{\rm helio}$.

Below we will discuss two limiting cases. In the first case the lack of rotation in the stars is taken as due to viewing the stellar disk face-on (Hunter et al. 2002). This would imply that the stars and gas lie in different planes. In the second case, we will assume that the stars are rotating at an inclination angle (68°) and a kinematical major axis (80°) that are the same as those of the HI gas.

There is some indirect evidence that the stars are not in the same plane as the neutral gas. In V-band, NGC 4449 has a boxy shape that becomes round in the outer parts, and there is a twisting of the isophotes from the central rectangle to the outer galaxy (see Figure 1). Hunter et al. (1999) interpret these characteristics as a bar structure that has a length of 3.9 disk scale-lengths. The shape of this bar is symmetrical in V, and to deproject this structure by a large angle (>30°) would produce a sharp-angled structure not seen in other IBm galaxies (Hunter & Elmegreen 2005) unless the line of nodes runs along the bar's major or minor axis. Our model for the inner gas disk has the line of nodes at PA 80°, almost halfway between the long and short axes of the bar. Thus, the stellar disk needs to be closer to face-on than the gas or tilted about a different axis. Furthermore, the bar in NGC

4449 has an apparent b/a of 0.6, a value that is typical of bars in IBm galaxies (Hunter & Elmegreen 2005). Deprojecting the bar by a large angle would produce an axis ratio that is not seen in IBm galaxies. Finally, if the bar in NGC 4449 is rotating, then the rotation speed along the bar's minor axis (PA of 316°) should be higher than the circular speed. To hide rotation at PA 316°, the stellar disk would need to be tilted about PA 46°. On the other hand, we do detect stellar absorption to the greatest extent along PA 46° and to the least extent along PA 316°. This is similar to the ionized gas which was best fit with a kinematic major axis at PA 46°. Thus, the two cases we are considering—a face-on disk and a disk inclined at 68° with a PA of 80°—most likely bracket the true orientation of the stellar disk.

4.2. Stellar velocity dispersion

Figures 3 and 4 show the observed velocity dispersions σ_{obs}. No trend with radius is clear except in PA 46° where the lowest σ_{obs} fall on the southwest side of the galaxy. Furthermore, differences in average σ_{obs} between PAs (1–4 km s^{-1}) are smaller than or comparable to the uncertainties (3–4 km s^{-1}). Therefore, we have averaged all of the measurements of σ_{obs} at all PAs together, weighted by uncertainty, and averaged the results of the two approaches to the measurements. The final average σ_{obs} is 29±2 km s^{-1}.

4.2.1. Case 1: Face-on Stellar Disk

In the case where we are looking at the stellar disk nearly face-on, σ_{obs} is simply the vertical component σ_z of σ_{tot}, where the total velocity dispersion σ_{tot} is the quadratic sum of the vertical component σ_z, the radial component σ_R, and the azimuthal component σ_ϕ. From the relationship between M_B and σ_z (Bottema 1993, Swaters 1999), we predict a σ_z of 29 km s^{-1} for NGC 4449. Thus, our observed σ_z is the same as predicted by the galaxy's luminosity.

In normal, well-mixed, axisymmetric disk systems in which the vertical scale height does not change with radius, the velocity dispersion drops with radius as the square-root of the surface density. In Figure 4 one can see that in NGC 4449 at R$\geq$ 56″ at PAs 46° and 271° the σ_{obs} are in fact lower than those in the central region. The average of σ_{obs} at radii less than 20″ in all PAs is 31±6 km s^{-1}, where the uncertainy of 6 km s^{-1} represents the range in values observed in the central region. If NGC 4449 were a well-behaved disk, we would then predict a σ_{obs} of 14±3 km s^{-1} at a radius of 69″. The average σ_{obs} at radii 56″ to 81″ is 19±4 km s^{-1}, where again the uncertainty represents the range of values measured there.

Although the uncertainties are large, we see that, within the uncertainties, the drop in σ_{obs} in the outer parts of the region we have observed is consistent with a normal face-on stellar disk.

4.2.2. Case 2: Inclined Stellar Disk

If the stellar disk is inclined, our σ_{obs} measured along some position angle is a combination of the three components of the velocity dispersion:

$$\sigma_{obs}^2 = (\sigma_R^2 \sin^2\eta + \sigma_\phi^2 \cos^2\eta)\sin^2 i + \sigma_z^2 \cos^2 i,$$

where η is the angle between the observed PA and the major axis and i is the inclination angle of the disk (e.g., Gerssen et al. 1997).

In the Milky Way and other spirals, the ratios of these three components are approximately constant with radius within a galaxy and similar between galaxies. Gerssen, Kuijken, & Merrifield (1997) measured $\sigma_z/\sigma_R\sim 0.7 \pm 0.2$ in the Sb galaxy NGC 488. From the data of Delhaye (1965) as presented by Binney & Merrifield (1998), giant stars in the solar neighborhood have $\sigma_z/\sigma_R\sim 0.73 \pm 0.09$. Other stellar components have similar ratios. For σ_ϕ and σ_R, the nearby red giants give a ratio of $\sigma_\phi/\sigma_R\sim 0.65 \pm 0.08$. Similarly, the epicyclic approximation and the observational determination of the Oort constants lead to the relation $\sigma_\phi^2/\sigma_R^2 = 0.5(1 + \frac{d\ln v}{d\ln R})$ (Binney & Tremaine 1987, Binney & Merrifield 1998), where v is the rotation speed at radius R, or $\sigma_\phi\sim 0.7\sigma_R$ where the galactic rotation curve is flat. These together suggest the approximate relationships $\sigma_z\sim\sigma_\phi\sim 0.7\sigma_R$.

How well these relations apply to NGC 4449 is not clear since this galaxy is dominated by a very large bar potential as identified in the optical by Hunter et al. (1999) and discussed in §4.1 above. This could result in non-circular motions, although such are not easily identified in the gas due to the complexity of the counter-rotation in the inner parts. However, to the extent that these relations do apply to NGC 4449, then along the major axis the dependence on the inclination drops out and $\sigma_{obs}\sim\sigma_z$, but at any other PA, a dependence on the inclination remains. For an inclination of 68° and kinematic major axis of 80°, σ_{obs} is 1.02, 1.13, and 1.27 times σ_z at the three PAs of the observations. The minimum value that we observe should occur at a PA of 271° and the maximum at PA 316°. This is opposite to what we see (31±3 km s^{-1} at PA 271° and 27±4 km s^{-1} at PA 316°), but the uncertainties are large. Thus, σ_z is most likely between 23 km s^{-1} and 28 km s^{-1}, for a σ_{obs} of 29 km s^{-1}. We adopt the average, and thus, σ_z is 25 km s^{-1} for this case.

5. Discussion

Because we wish to define the structure of NGC 4449 from its stellar kinematic properties, we must evaluate the ratio of the rotation speed to the velocity dispersion V/σ. Since we wish to compare V/σ measured in NGC 4449 to values measured in other galaxies, it is important that we measure V and σ in the same way. For elliptical galaxies, Bender et al. (1994) used σ_{obs} averaged within a radius of 0.5R$_e$, where R$_e$ is the effective radius, and Pinkney et al. (2003) used σ_{obs} measured in the center of early type galaxies. Bottema's (1993) observations of a sample of spirals indicate that σ_R at a radius of one scale-length is similar in value to σ_z at the center of the galaxy. They used both of these quantities. Vega Beltrán et al. (2001) give σ_{obs} at 0.25R$_e$ for spirals. Thus, the quantity that makes the most sense to use here is σ_z measured in the central region of NGC 4449. For V in the ratio V/σ, all of the references mentioned above use the maximum rotation speed V_{max} of the system. Therefore, we should use V_{max}/σ_z for NGC 4449.

Unfortunately, we did not reliably measure rotation in the stars. However, the gas does show clear rotation. Even if the stars and gas lie in different planes, we would expect that they see nearly the same gravitational potential. That this is a reasonable assumption is shown in observations of polar ring galaxies where the maximum rotation speed in the disk is the same as that in the ring to within 25–35% (Sackett et al. 1994, Swaters & Rubin 2003). Therefore, it seems likely that the maximum rotation speed of the stars in NGC 4449 is no more than V_{max} for the gas, which was 80 km s^{-1} in our model.

The uncertainty in the ratio V_{max}/σ_z is dominated by the uncertainty in the stellar V_{max}, not in the effect of inclination of the disk on the measurement of σ_z. Thus, for both of our cases, a V_{max} of 80 km s^{-1} implies a V_{max}/σ_z of 3. For spiral galaxies V/σ is measured to be 2–5 while for ellipticals, this ratio is less than one. Therefore, NGC 4449's value of V/σ is like those measured in spiral galaxies and implies that NGC 4449 also has a kinematically relatively cold disk. In addition, since σ_z drops radially in disks, it is unlikely that the stars further out in the disk of NGC 4449 have a higher velocity dispersion than those in the central region, and Figure 4 seems to be consistent with this.

Of course, the rotation speed of the stars is not known, and it could be *lower* than that of the gas if more kinetic energy is going into random motions than into ordered rotation. The fact that we measured a value for σ_z that was predicted for NGC 4449 by its M$_B$ suggests that the velocity dispersion of the stars is not extraordinarily high. Furthermore, the velocity dispersion of the gas within the optical part of NGC 4449 (20 km s^{-1}, Hunter et al. 1999) is comparable to the stellar velocity dispersion, making it unlikely that there is an appreciable asymmetric drift of the stars relative to the mean rotation velocity of the gas. For NGC 4449 to have a ratio V/σ that is minimally comparable to that of triaxial systems,

the stellar V_{max} would have to be one-third that of the gas.

For an isothermal stellar population with a constant velocity dispersion in a dark halo, in the outer galaxy $h_z/R \sim \sigma_z/v_c$ where v_c is the circular velocity and h_z is the disk scale-height. On the other hand, for a self-gravitating disk with constant velocity, near the center of the disk $h_z/R \sim (\sigma_z/v_c)^2$ (Binney & Merrifield 1998). This suggests that the intrinsic minor-to-major axis ratio $(b/a)_0$ of the NGC 4449 stellar disk lies in the range 0.3–0.6. A value of 0.3–0.4 has been deduced for Im galaxies by Hodge & Hitchcock (1966) and van den Bergh (1988) from studies of observed b/a distributions, and a value of 0.6 has been suggested by Staveley-Smith et al. (1992).

There are two other Im/Sm galaxies that have measures of V_{max}/σ_z. For the LMC, this ratio is 3 (van der Marel et al. 2002; see also Nikolaev et al. 2004), and in NGC 2552 it is 5 (Swaters 1999). Thus, these galaxies also have ratios that imply that they have flattened kinematically cold disks. However, we note that the three galaxies that have now been observed are at the high end of the range of M_B of Im galaxies, in the region that overlaps with late-type spirals. Perhaps more typical, lower luminosity Im galaxies are shaped differently.

It is also of interest to examine the local value of the ratio V/σ_z. For NGC 4449, our measurement of σ_{obs} applies to the inner $1'$. In our model of the HI kinematics, the circular velocity ramps linearly from 0 to 80 km s^{-1} between the center and $2.5'$. Thus, the maximum rotation speed at a radius of $1'$ is about 32 km s^{-1}. We experimented with tweaking the model to see if the circular velocity could remain high closer into the center, and found that such was not consistent with the HI observations. So, for the case of a stellar disk seen nearly face-on, $(V/\sigma_z)_{R=1'}$ is 1.1. If the stars are rotating in a disk seen at an inclination of 68°, the observed gradient discussed in Section 4 implies a rotation speed of only 12 km s^{-1} at a radius of $1'$. With a σ_z of 25 km s^{-1}, the ratio $(V/\sigma_z)_{R=1'}$ is 0.5. In either case the mean rotation velocity is comparable to or less than the velocity dispersion of the stars in the central 1.3 disk scale-lengths of NGC 4449.

6. The future of NGC 4449

In Hunter et al. (2002) we constructed a simple model for the distribution of HI and ionized gas in NGC 4449, in which the gas is in orbits of constant inclination to the plane of the sky, but with precession-induced twisting of the line of nodes. Dynamically, this is what we would expect for a tilted gas disk precessing in a gravitational potential that is roughly axisymmetric and flattened with its midplane in the plane of the sky (as the stellar disk

appears to be). What does this model imply for the current age and the future development of the twisted gas disk?

Our model gas disk is inclined at 68° to face-on, and twists through 180° about the line of sight. To fit the HI measurements, we took the rotation curve to rise linearly to 80 km s^{-1} at 2.5′ or 3 kpc from the center. Thus, within $R = 2.5'$, the angular rate of rotation $\Omega_{rot} = [80\text{km/s}]/[3\text{ kpc}] \approx 27\text{ Gyr}^{-1}$ and the rotation period is 250 Myr. Beyond that the rotation curve is flat, so the rotation rate Ω_{rot} is proportional to $1/R$.

An orbit tilted at angle θ to the equatorial plane of the potential precesses at a rate $\Omega_{rot}\epsilon_\Phi \cos(\theta)$, where ϵ_Φ is the flattening of the equipotential contours. From Section 2.2.2 of Binney & Tremaine (1987), we expect the equipotentials to be roughly a third as flattened as the density contours. The total mass distribution is unlikely to be *more* flattened than the stellar distribution, which has an axis ratio $b/a = 0.3-0.6$; thus $\epsilon_\Phi \approx 0.33(1-b/a) = 0.1-0.2$. Setting $\theta = 68°$, this corresponds to a precession period of 3–7 Gyr within 2.5′, decreasing as $1/R$ at larger radii.

Our model fits the HI distribution within 12′. The gas orbits twist by 190° between radii of 2′ and 5′, and have a constant orientation further out. Our model is the simplest that fits the HI velocities, and more likely the real twist is more gradual. If the entire gas disk was originally coplanar, it would take 2–3 Gyr to develop a twist of 190° between gas orbiting at 2′ and that at 10′. If we take this as a very rough indication of the structure's age, it is consistent with the dynamical model of Theis & Kohle (2001) for the outer gas disk. They suggest (Section 4.2) that the HI disk may have originated in an encounter with neighbor NGC 4736 roughly 4 Gyr ago; a close passage by the dwarf DDO 125 0.5 Gyr ago perturbed the gas disk but is unlikely to have been its origin.

In another 2–3 Gyr, the part of the disk within 2′ will have twisted by 360° relative to that beyond 5′. Beyond that time, we might no longer recognize the entire structure as a smoothly-twisted disk. Instead, we would probably interpret it as a broad HI ring, with disconnected clouds of gas in variously inclined orbits nearer to the galaxy center.

We are grateful to the people at KPNO who helped make these observations successful, and especially to Daryl Willmarth who recommended a more efficient instrument setup than we had originally planned. We are also extremely thankful to Phil Massey who assisted in the observations. L.S.S. is grateful for hospitality at the Max-Planck-Institute for Astrophysics in Garching. Funding for this work was provided in part by the National Science Foundation through grants AST-02-04922 to D.A.H. and AST-00-98419 to L.S.S.

Facilities: Lowell Observatory, KPNO.

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Fig. 1.— False-color representation of the logarithm of the V-band and Hα images of NGC 4449 (Hunter et al. 1999). In both images lines are drawn along the three observed position angles PA: 46°, 316°, and 271°. The extent of the lines indicates the region of the slit over which measurements of the stellar velocity dispersion and heliocentric velocity were made. The circles mark the center of the galaxy.

Fig. 2.— Stellar line of sight heliocentric radial velocities V_{helio} measured from absorption lines in each spectrum of NGC 4449. The two approaches to measuring the spectra are discussed in Section 3. The position from the center of the galaxy is measured along the slit, and positive numbers refer to the direction given by the position angle PA. The solid horizontal line is the adopted central velocity of 205 km s^{-1}. The dashed line is the fit to the rotation velocities of the ionized gas at PA 46° by Hunter et al. (2002). The measurements of Hunter et al. (2002) are also included, with their results at 136° and 91° flipped to match the PAs used here. An offset of 9 km s^{-1} has been subtracted from the Hunter et al. measurements to account for the difference in central velocity that was used. The PAs corresponding to the major and minor axes of the bar are noted.

Fig. 3.— Observed stellar velocity dispersion σ_{obs} of absorption lines measured from the cross-correlation profiles for each spectrum of NGC 4449. The solid horizontal line denotes the uncertainty-weighted average of all of the measured dispersions. The σ_{obs} are determined from the cross-correlation FWHM and corrected for the intrinsic resolution as given by the template stars. The two approaches to measuring the spectra discussed in Section 3 are plotted in different colors. The PAs corresponding to the major and minor axes of the bar are noted.

Fig. 4.— Same as Figure 3, but measurements of the observed velocity dispersion σ_{obs} along different position angles PA are plotted together as a function of distance from the center of the galaxy. PA 46° is the morphological major axis of the bar and PA 316° is the bar minor axis. The two approaches to measuring the spectra discussed in Section 3 are plotted in different colors.